Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G37646.1

Mediterranean outflow pump: An alternative mechanism for the Lago-mare and the end of the Messinian Salinity Crisis

Alice Marzocchi[1*], Rachel Flecker[1], Christiaan G. C. van Baak[2], Daniel J. Lunt[1], and Wout Krijgsman[2]

[1]*School of Geographical Sciences, University of Bristol, Bristol, UK*

[2]*Paleomagnetic Laboratory Fort Hoofddijk, Department of Earth Sciences, Utrecht University, Utrecht, Netherlands*

[*]*Now at: Dept. of the Geophysical Sciences, The University of Chicago, Chicago, USA*

ABSTRACT

The final stage of the Messinian Salinity Crisis (MSC) is characterized by brackish water "Lago-mare" conditions in the intermediate and marginal basins of the Mediterranean Sea. The presence of Paratethyan (former Black Sea) fauna in these deposits has fuelled long-lasting controversies over the connectivity between the Mediterranean and Paratethys and contemporary sea level drops in both basins. Here, we use the results of sub-precessional climate simulations to calculate the freshwater budget of the Mediterranean and Paratethys in the Messinian. We show that, during the MSC, the freshwater budget of Paratethys was positive, while the Mediterranean was negative. Using these numerical constraints, we propose a Mediterranean outflow pump as an alternative scenario for the two most dramatic hydrological changes in the MSC: first the Halite-Lago-mare transition and then the Pliocene reestablishment of marine conditions.

Following the maximum MSC low-stand during halite formation, progressive Mediterranean sea-level rise resulting from African river runoff and overspill from both the Atlantic and Paratethys eventually reached the level of the Paratethys sill. A density contrast at this gateway caused dense Mediterranean waters to flow into the Paratethys, driving a compensatory return flow. This "pump" mechanism significantly enhanced Paratethyan inflow to the Mediterranean, creating suitable conditions for the Lago-mare fauna to migrate and thrive. When the Mediterranean sea level finally reached the height of the Gibraltar sill, Mediterranean outflow restarted there and enhanced exchange with the Atlantic. During this reorganisation of the circulation, brackish and hypersaline waters were pumped out of the Mediterranean, and open marine conditions were re-established without major flooding of the basin at the Mio-Pliocene boundary.

INTRODUCTION

Catastrophic events are commonly invoked to explain major changes in Earth's history and they dominate both the scientific and popular literature. In many cases, however, interpretation of the evidence is controversial, resulting in enduring debates. A key example is the Messinian Salinity Crisis (MSC; 5.971–5.33 Ma; Roveri et al., 2014 and references therein), where hypersaline and brackish water deposits are thought to have precipitated in a 1500 m deep desiccated Mediterranean basin (e.g., Hsü et al., 1973). The initial hypothesis to explain the brackish "Lago-mare" conditions toward the end of the MSC, is that shallow lakes existed both at the bottom of the desiccated Mediterranean and all around its perched margins (e.g., Orszag-Sperber, 2006). The hypothesized basin-wide low-stand is still subject to debate (e.g., Roveri et al., 2014;

Lugli et al., 2015; Popescu et al., 2015) and an alternative scenario suggests that the Mediterranean Sea became a deep, low-salinity lake comparable to the present-day Caspian Sea (McCulloch and De Deckker, 1989; Grossi et al., 2008). In both scenarios, the presence of a brackish water environment in the Mediterranean Sea is commonly explained by either fresh water capture from Paratethys, the precursor lake that comprised both the Black and Caspian seas (Fig. 1), or enhanced precipitation and runoff (e.g., Hsü et al., 1973; Orszag-Sperber, 2006). The occurrence of Paratethyan ostracods, molluscs and dinoflagellates in the Lago-mare deposits indicates fresh water input from the Black Sea (e.g., Gliozzi et al., 2007; Stoica et al., 2016), but the sediments also contain marine fish suggesting coeval influx of Atlantic water (e.g., Carnevale et al., 2006).

Repercussions of the Mediterranean MSC scenario have also been extended to the Paratethys basins, with latest Miocene sea level drops of more than 1000 m inferred for the Black and Caspian seas (e.g., Hsü and Giovanoli, 1979; Jones and Simmons, 1996). Alternative scenarios where the Paratethyan basins are full and overspilling have also been suggested (e.g., Popov et al., 2006; van Baak et al., 2015). In this study, we bring a new perspective to the interpretation of these Messinian events, by calculating the freshwater hydrologic budgets of the Mediterranean, Black and Caspian seas based on climate model simulations for the late Miocene. We test these hypotheses for full or desiccated basins during the MSC and explore the implications of our results for connectivity between the Mediterranean and Paratethys. Finally, we propose an alternative scenario for the abrupt reestablishment of marine conditions after the end of the MSC, which does not require the invoked waterfall-like Zanclean flooding (e.g., Hsü et al., 1973; McKenzie, 1999) at the Mio-Pliocene boundary.

METHODS

During the Messinian, river runoff to the Mediterranean Sea was dominated by monsoonal rainfall from North Africa, which is strongly modulated by orbital forcing, mainly precession (Marzocchi et al., 2015). We therefore performed the hydrologic calculations presented here on the results of 22 climate simulations through a Messinian precessional cycle. The experiments were carried out with a global general circulation model (HadCM3L); a description of the late Miocene model configuration can be found in Bradshaw et al. (2012) and the full Messinian sub-precessional experimental design is detailed in Marzocchi et al. (2015). In this orbital ensemble, simulations are spaced by a thousand years and forced with orbital parameters from a real precession cycle at 6.56–6.58 Ma. This cycle has significant but not extreme amplitude and can, therefore, be considered representative of the average sub-precessional variations throughout the Messinian period. A pre-MSC cycle was used in order to compare model output with astronomically tuned faunal data for this time slice; this is not possible during the MSC itself because palaeoclimatological proxy records and independent biozones are absent, due to the extreme environmental conditions.

Here, for each simulation from the orbital ensemble we calculate precipitation and evaporation for the Mediterranean and Paratethys catchments. The area is divided into drainage basins (Fig. 1) following Gladstone et al. (2007). We also include the Amu Darya catchment and consider the Black Sea and Caspian Sea both separately and

DOI:10.1130/G37646.1

connected as a single Paratethyan lake. We calculate the net hydrologic fluxes and the resulting freshwater budget in each basin, following the same methodology as Gladstone et al. (2007).

The late Miocene palaeogeography used in the numerical simulations of Marzocchi et al., (2015) is representative of the Paratethys configuration during the early Messinian. Reconstructions based on the analysis of Paratethyan facies and biogeographic records of marine and terrestrial biota, suggest that during the MSC both the Black and Caspian seas had smaller surface areas (e.g., Popov et al., 2006). We therefore perform our hydrologic calculations over a reduced surface area for the Paratethys (Fig. 1).

SUB-PRECESSIONAL HYDROLOGIC CHANGES

A clear precessional signal dominates the simulated Mediterranean freshwater budget, while Paratethys shows no evident orbital variations (Fig. 2). This suggests that the regular alternations observed in the Messinian geological record of the Black Sea, which have previously been linked to precessional cyclicity (e.g., van Baak et al., 2015 and references therein), are probably a transferred signal driven by exchange with the Mediterranean Sea.

Our hydrologic calculations indicate that throughout the simulated precession cycle the annual freshwater budget of both the Black and Caspian seas is always positive (mean ~3.1 and 3.4×10^{14} l yr^{-1}, respectively). The hypothesized 1–2 km sea level fall in the Caspian Sea (e.g., Jones and Simmons, 1996) and Black Sea (e.g., Hsü and Giovanoli, 1979) during the Messinian are not compatible with these calculated positive freshwater

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G37646.1

budgets. The freshwater budget of Paratethys as a whole is strongly positive in our calculations (mean ~6.5×10^{14} l yr^{-1}), indicating that it was a significant source of fresh water input for the Mediterranean in the Messinian.

Despite significant freshwater input from North African rivers, the Mediterranean Sea's freshwater budget is strongly negative (mean ~-1.9×10^{15} l yr^{-1}) throughout the simulated precession cycle (Fig. 2), as a result of latitudinally-driven net evaporative loss, even with the additional contribution from the Paratethys (Fig. 2). This indicates that Atlantic inflow is required to prevent the Mediterranean sea level from falling, which is equivalent to the estimates obtained by Ryan (2008). Today, the freshwater deficit over the Mediterranean Sea is ~0.04 Sv (e.g Bryden et al., 1994; 1 Sv = 10^6 m^3 s^{-1}) and it is balanced by inflow from the Atlantic through the Straits of Gibraltar.

In the Messinian, assuming the Mediterranean was receiving the excess freshwater from the Paratethys (0.02 Sv), it had a similar freshwater deficit as today (mean of 0.04 Sv through the simulated precession cycle; Fig. 2). For Mediterranean sea level to have fallen during the MSC, Atlantic inflow must have been less than 0.04 Sv. The consequences of the resulting sea level drop would have been erosion of the margins (Messinian Erosional Surface, Lofi et al., 2005; Fig. 3) and, once the Mediterranean was below the level of the sill, cessation of outflow and associated rising brine concentration, which ultimately reached halite saturation (Krijgsman and Meijer, 2008). By contrast, for the Mediterranean to be full, Atlantic inflow must be ≥ 0.04 Sv. Atlantic inflow today (0.7–0.8 Sv; e.g., Bryden et al., 1994) is an order of magnitude larger than the inflow required to compensate for the freshwater deficit, because it also replaces the substantial volume of water flowing out of the Mediterranean. It is not possible to constrain past

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G37646.1

Mediterranean outflow from our climate simulations, but some inferences about Mediterranean-Atlantic exchange during the last phase of the MSC can be drawn by combining our simulated climatic constraints with the Messinian geological record.

AN ALTERNATIVE SCENARIO FOR THE FINAL STAGE OF THE MSC

The current stratigraphic model describes two distinct phases during the last stage of the MSC (stage 3; Roveri et al., 2014 and references therein). Immediately above the Halite (stage 2) are the Upper Evaporites (stage 3.1; 5.55–5.42 Ma) which typically comprise gypsum-marl alternations (e.g., Sicily; Manzi et al., 2009), while the top layer (stage 3.2; 5.42–5.33 Ma) is characterized by highly variable sediments, including both evaporites and fossil-bearing clastics (Lago-mare; e.g., McCulloch and De Deckker, 1989). Where found, both in deep and marginal settings, faunal assemblages are generally dominated by a small number of ostracods that tolerate a wide range of salinities, mainly *Cyprideis* and *Loxoconcha* genera, but toward the very top of the succession the biodiversity increases (Gliozzi et al., 2007) and closely resembles the brackish-water Paratethyan fauna of the Black Sea margin (Stoica et al., 2016 and references therein).

It has been calculated that in order to precipitate the thick (> 1 km) halite deposits from MSC stage 2, a reduced but continuous inflow from the Atlantic would have been required in combination with blocked outflow (Krijgsman and Meijer, 2008). On the basis of the numerical constraints provided by the model, we suggest that during stage 2 Atlantic inflow was less than 0.04 Sv, resulting in a Mediterranean sea level significantly below the height of the connection with the Atlantic (Fig. 3a), which led to halite

DOI:10.1130/G37646.1

precipitation in the deep basins (Roveri et al., 2014 and references therein). A significant sea level drop (the extent is unknown and largely debated; e.g. Christeleit et al., 2015 and references therein) in the Mediterranean Sea during the Halite phase fits our hydrologic calculations and it is envisaged up to and including this stage. However, the presence of a basin-wide connecting water body is necessary to justify the occurrence of Black Sea ostracods in the Spanish marginal basins during the Lago-mare stage, which are not merely related to Paratethyan forms, but belong to the same species (Stoica et al., 2016).

MSC Stage 3.1

At the beginning of the final stage of the MSC, Mediterranean sea level was still below the Atlantic connection and inflow was therefore slightly below 0.04 Sv (Fig. 3b). Atlantic inflow may have increased gradually through this period, perhaps as a result of headward erosion of the Alboran-Atlantic connection (e.g., Loget et al., 2005). However, even if this was not the case, given the reduced surface area of the partially desiccated Mediterranean, an Atlantic inflow slightly below 0.04 Sv would have caused progressive refilling of the basin. The Atlantic inflow envisaged is equivalent to a large marine river equivalent in scale to ~1/5 of the Amazon (mean annual discharge of ~200000 m^3 s^{-1}) flowing through the Alboran Basin, where there is some evidence that marine conditions persisted during the MSC (e.g., Melilla section; Cornée et al., 2002). Additional overspill from Paratethys (0.02 Sv) and precessionally enhanced input from North African rivers (Fig. 2) contributed low salinity water to form a stratified layer above the halite brine. At this stage, the resulting salinity was still too high to support normal marine or brackish-water faunal assemblages, but allowed opportunistic ostracod taxa like *Cyprideis*, which tolerate much higher salinities (~2–120 g kg^{-1}; e.g., Gitter et al., 2015 and references therein), to thrive Mediterranean-wide from MSC stage 3.1. As a consequence, these species have been recovered in deposits from both deep and marginal settings (e.g. Stoica et al., 2016 and references therein).

Lago-mare

Once rising Mediterranean sea level reached the height of the Paratethys sill, Mediterranean outflow to Paratethys would have been initiated as a result of the density contrast between the two basins, increasing the inflow from Paratethys above 0.02 Sv (Fig. 3c). It is not clear how much Paratethyan water might have flowed into the Mediterranean via this mechanism, but a maximum estimate is the total volume of the present day Black and Caspian seas, which, if spread across the Mediterranean Sea's surface area, would result in a fresh-water layer ~250 m thick. This freshwater pulse, combined with enhanced North African river run off during insolation maxima, could have resulted in a Mediterranean-wide hydrological reconfiguration (e.g., Roveri et al., 2014). The resulting strongly stratified water column (Fig. 3c) would have ranged from deep water brines, through intermediate marine waters fed by Atlantic inflow, to shallow water brackish conditions suitable for the migration of diverse faunal assemblages from the Paratethys (Stoica et al., 2016). In some deep settings where salinities were too high, sharp transitions from evaporitic sediments to normal marine sediments, and lack of Lago-mare deposits, are also possible.

This scenario can explain the synchronous presence of marine indicators (e.g., Atlantic fish, Carnevale et al., 2006; small foraminifera, Iaccarino et al., 2008) in the

Lago-mare deposits, and the widespread occurrence of brackish water Paratethyan fauna in the Mediterranean's marginal basins (e.g., Malaga, Nijar, Viera - Spain, Stoica et al., 2016 and references therein; Appenines - Italy, Cosentino et al., 2012; Crete, Cyprus; Grossi et al., 2008). The location and dimensions of the Mediterranean-Paratethys sill during the MSC are unknown, but for this mechanism to account for the widespread occurrence of Paratethyan fauna in the Mediterranean marginal basins, the sea level must have been high enough for the Mediterranean Sea to be close to full, but still lower than the Mediterranean-Atlantic sill (Fig. 3c).

Mio-Pliocene Boundary

In this scenario, the switch to marine conditions in the Mediterranean at 5.33 Ma does not result from a quick flooding event (e.g., McKenzie, 1999), but is rather the result of progressive refilling of the basin (e.g., Cornée et al., 2016; Loget et al., 2005). The abrupt environmental transition at the Mio-Pliocene boundary could be achieved by Mediterranean sea level reaching the height of the Atlantic sill, triggering Mediterranean outflow into the Atlantic and driving a dramatic (up to an order of magnitude) rise in Atlantic inflow. This was likely enough to break down Mediterranean water column stratification and kick-start overturning circulation in the basin, eventually restoring normal marine conditions (Fig. 3d).

Rapid changes in the patterns of gateway exchange as envisaged here are not improbable. Today, transitions from two to three-layer flow in the Bab el Mandeb Strait that links the Red Sea and the Gulf of Aden, occur on seasonal timescales (e.g., Smeed, 2004). However, a critical test of the Mediterranean-Paratethys outflow pump hypothesis for the Lago-mare is the Paratethyan geological record for this interval. DSDP 380/380A holes in the Black Sea basin bear evidence of a sea level rise at around 5.4 Ma (van Baak et al., 2015) and the sedimentary successions of the Dacian basin also show a coeval transgression (Stoica et al., 2013). A high-resolution salinity proxy record is required to establish in detail how Paratethys environments would have changed as a result of the outflow pump mechanism. Evidence for the onset of Mediterranean outflow to Atlantic at the Mio-Pliocene boundary is more conclusive and can be observed in both seismic profiles and drill core records (IODP Expedition 339; van der Schee et al., 2016).

In conclusion, we suggest that the abrupt, high amplitude changes in environmental conditions during the final stage of the MSC were driven by a Mediterranean outflow pump mechanism. This significantly enhanced the overspill of Paratethyan water during the Lago-mare and of Atlantic inflow during the Pliocene into the Mediterranean basin. Consequently, we argue that the end of the MSC was not caused by catastrophic flooding at the Mio- Pliocene boundary, but by the reorganisation of circulation patterns and the establishment of Mediterranean-Atlantic exchange similar to today.

ACKNOWLEDGMENTS

We thank Dirk Simon and Paul Meijer for useful discussions and Mike Rogerson and Malte Jansen for suggestions on Figure 2. This work was funded by the People Programme of the European Union’s 7th Framework Programme FP7/2007–2013/ under REA Grant Agreement No. 290201 MEDGATE.

REFERENCES CITED

Bradshaw, C.D., Lunt, D.J., Flecker, R., Salzmann, U., Pound, M.J., Haywood, A.M., and Eronen, J.T., 2012, The relative roles of CO_2 and palaeogeography in determining late Miocene climate: Results from a terrestrial model–data comparison: Climate of the Past, v. 8, p. 1257–1285, doi:10.5194/cp-8-1257-2012.

Bryden, H.L., Candela, J., and Kinder, T.H., 1994, Exchange through the Strait of Gibraltar: Progress in Oceanography, v. 33, p. 201–248, doi:10.1016/0079-6611(94)90028-0.

Carnevale, G., Caputo, D., and Landini, W., 2006, Late Miocene fish otoliths from the Colombacci Formation (Northern Apennines, Italy): Implications for the Messinian 'Lago-mare'event: Geological Journal, v. 41, p. 537–555, doi:10.1002/gj.1055.

Christeleit, E.C., Brandon, M.T. and Zhuang, G., 2015. Evidence for deep-water deposition of abyssal Mediterranean evaporites during the Messinian salinity crisis: Earth and Planetary Science Letters, *427*, p. 226-235. doi:10.1016/j.epsl.2015.06.060.

Cornée, J.J., Roger, S., Münch, P., Saint Martin, J.P., Féraud, G., Conesa, G., and Pestrea-Saint Martin, S., 2002, Messinian events: New constraints from sedimentological investigations and new 40 Ar/39 Ar ages in the Melilla–Nador Basin (Morocco): Sedimentary Geology, v. 151, p. 127–147, doi:10.1016/S0037-0738(01)00235-4.

Cornée, J.J., Münch, P., Achalhi, M., Merzeraud, G., Azdimousa, A., Quillévéré, F., Melinte-Dobrinescu, M., Chaix, C., Moussa, A.B., Lofi, J. and Séranne, M., 2016. The Messinian erosional surface and early Pliocene reflooding in the Alboran Sea:

New insights from the Boudinar basin, Morocco: Sedimentary Geology, 333, p.115-129. doi:10.1016/j.sedgeo.2015.12.014.

Cosentino, D., Bertini, A., Cipollari, P., Florindo, F., Gliozzi, E., Grossi, F., Mastro, S.L., and Sprovieri, M., 2012, Orbitally forced paleoenvironmental and paleoclimate changes in the late postevaporitic Messinian of the central Mediterranean Basin: Geological Society of America Bulletin, v. 124, p. 499–516, doi:10.1130/B30462.1.

Gitter, F., Gross, M., and Piller, W.E., 2015, Sub-Decadal Resolution in Sediments of Late Miocene Lake Pannon Reveals Speciation of Cyprideis (Crustacea, Ostracoda): PLoS One, v. 10, p. e0109360, doi:10.1371/journal.pone.0109360.

Gladstone, R., Flecker, R., Valdes, P., Lunt, D., and Markwick, P., 2007, The Mediterranean hydrologic budget from a Late Miocene global climate simulation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 251, p. 254–267, doi:10.1016/j.palaeo.2007.03.050.

Gliozzi, E., Ceci, M.E., Grossi, F., and Ligios, S., 2007, Paratethyan ostracod immigrants in Italy during the Late Miocene: Geobios, v. 40, p. 325–337, doi:10.1016/j.geobios.2006.10.004.

Grossi, F., Cosentino, D., and Gliozzi, E., 2008, Late Messinian Lago-Mare ostracods and palaeoenvironments of the central and eastern Mediterranean Basin: Bollettino della Società Paleontologica Italiana, v. 47, p. 131–146.

Hsü, K.J., Ryan, W.B.F., and Cita, M.B., 1973, Late Miocene desiccation of the Mediterranean: Nature, v. 242, p. 240–244, doi:10.1038/242240a0.

Hsü, K.J., and Giovanoli, F., 1979, Messinian event in the Black Sea: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 29, p. 75–93, doi:10.1016/0031-0182(79)90075-0.

Iaccarino, S.M., et al., 2008, The Trave section (Monte dei Corvi, Ancona, Central Italy): An integrated paleontological study of the Messinian deposits: Stratigraphy, v. 5, p. 281–306.

Jones, R.W., and Simmons, M.D., 1996, A review of the stratigraphy of Eastern Paratethys (Oligocene-Holocene): Bulletin of the Natural History Museum Geology Series, v. 52, p. 25–50.

Lofi, J., Gorini, C., Berné, S., Clauzon, G., Dos Reis, A.T., Ryan, W.B., and Steckler, M.S., 2005, Erosional processes and paleo-environmental changes in the Western Gulf of Lions (SW France) during the Messinian Salinity Crisis: Marine Geology, v. 217, p. 1–30, doi:10.1016/j.margeo.2005.02.014.

Loget, N., Driessche, J.V.D., and Davy, P., 2005, How did the messinian salinity crisis end?: Terra Nova, v. 17, p. 414–419, doi:10.1111/j.1365-3121.2005.00627.x.

Lugli, S., Manzi, V., Roveri, M., and Schreiber, B.C., 2015, The deep record of the messinian salinity crisis: Evidence of a non-desiccated mediterranean sea: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 297, p. 83–99.

Manzi, V., Lugli, S., Roveri, M., and Schreiber, B.C., 2009, A new facies model for the Upper Gypsum of Sicily (Italy): Chronological and palaeoenvironmental constraints for the Messinian salinity crisis in the Mediterranean: Sedimentology, v. 56, p. 1937–1960, doi:10.1111/j.1365-3091.2009.01063.x.

Marzocchi, A., Lunt, D.J., Flecker, R., Bradshaw, C.D., Farnsworth, A., and Hilgen, F.J., 2015, Orbital control on late Miocene climate and the North African monsoon: Insight from an ensemble of sub-precessional simulations: Climate of the Past, v. 11, p. 1271–1295, doi:10.5194/cp-11-1271-2015.

McCulloch, M.T., and De Deckker, P., 1989, Sr isotope constraints on the Mediterranean environment at the end of the Messinian salinity crisis: Nature, v. 342, p. 62–65, doi:10.1038/342062a0.

McKenzie, J.A., 1999, From desert to deluge in the Mediterranean: Nature, v. 400, p. 613–614, doi:10.1038/23131.

Krijgsman, W. and Meijer, P.T., 2008, Depositional environments of the Mediterranean “Lower Evaporites” of the Messinian salinity crisis: Constraints from quantitative analyses: Marine Geology, v. 253(3), p.73–81, doi:10.1016/j.margeo.2008.04.010.

Orszag-Sperber, F., 2006, Changing perspectives in the concept of “Lago-Mare” in Mediterranean Late Miocene evolution: Sedimentary Geology, v. 188–189, p. 259–277, doi:10.1016/j.sedgeo.2006.03.008.

Popescu, S.M., Dalibard, M., Suc, J.P., Barhoun, N., Melinte-Dobrinescu, M.C., Bassetti, M.A., Deaconu, F., Head, M.J., Gorini, C., Do Couto, D. and Rubino, J.L., 2015. Lago Mare episodes around the Messinian–Zanclean boundary in the deep southwestern Mediterranean: Marine and Petroleum Geology, 66, p.55-70.

Popov, S.V., Shcherba, I.G., Ilyina, L.B., Nevesskaya, L.A., Paramonova, N.P., Khondkarian, S.O., and Magyar, I., 2006, Late Miocene to Pliocene palaeogeography of the Paratethys and its relation to the Mediterranean:

Palaeogeography, Palaeoclimatology, Palaeoecology, v. 238, p. 91–106, doi:10.1016/j.palaeo.2006.03.020.

Roveri, M., et al., 2014, The Messinian Salinity Crisis: past and future of a great challenge for marine sciences: Marine Geology, v. 352, p. 25–58, doi:10.1016/j.margeo.2014.02.002.

Ryan, W.B., 2008, Modelling the magnitude and timing of evaporative drawdown during the Messinian salinity Crisis: Stratigraphy, v. 5(1), p.227-243.

Smeed, D.A., 2004, Exchange through the Bab el Mandab: Deep-sea Research. Part II, Topical Studies in Oceanography, v. 51, p. 455–474, doi:10.1016/j.dsr2.2003.11.002.

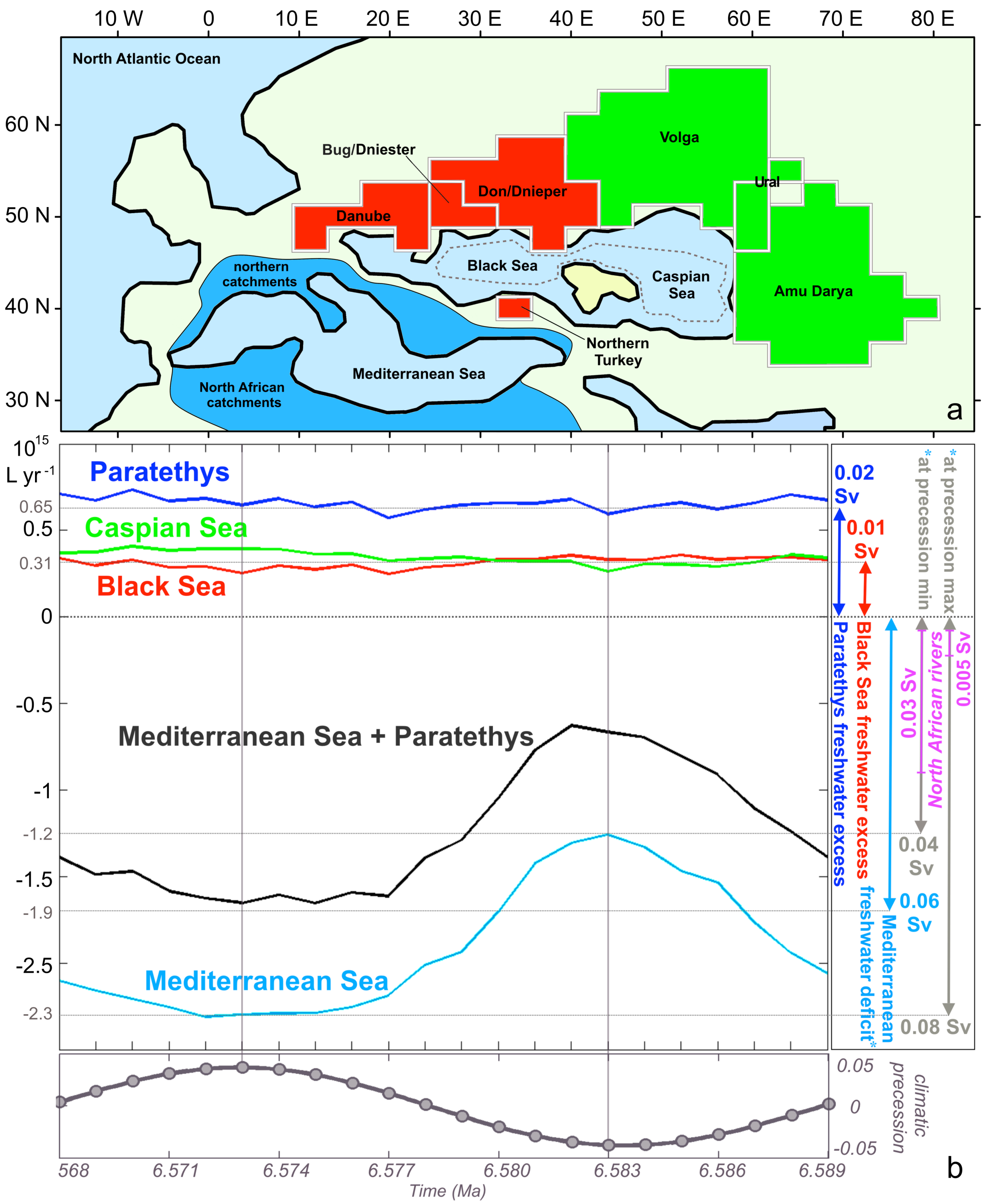
Stoica, M., Lazăr, I., Krijgsman, W., Vasiliev, I., Jipa, D., and Floroiu, A., 2013, Paleoenvironmental evolution of the East Carpathian foredeep during the late Miocene–early Pliocene (Dacian Basin; Romania): Global and Planetary Change, v. 103, p. 135–148, doi:10.1016/j.gloplacha.2012.04.004.

Stoica, M., Krijgsman, W., Fortuin, A., and Gliozzi, E., 2016, Paratethyan ostracods in the Spanish Lago-Mare: More evidence for interbasinal exchange at high Mediterranean sea level: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 441, p. 854–870, doi:10.1016/j.palaeo.2015.10.034.

van Baak, C.G., Radionova, E.P., Golovina, L.A., Raffi, I., Kuiper, K.F., Vasiliev, I., and Krijgsman, W., 2015, Messinian events in the Black Sea: Terra Nova, v. 27, p. 433–441, doi:10.1111/ter.12177.

van der Schee, M., Sierro, F.J., Jiménez-Espejo, F.J., Hernández-Molina, F.J., Flecker, R., Flores, J.A., Acton, G., Gutjahr, M., Grunert, P., García-Gallardo, Á. and

Andersen, N., 2016. Evidence of early bottom water current flow after the Messinian Salinity Crisis in the Gulf of Cadiz: Marine Geology (in press).



Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G37646.1

Figure 1. (a) Drainage basins for the Black (red) and Caspian (green) seas. The Mediterranean Sea drainage basins are defined as in Gladstone et al. (2007) and schematic here. Dashed in gray is the reduced Paratethys surface area used for the Messinian hydrologic calculations. (b) Freshwater budget for Paratethys, Mediterranean, Caspian and Black seas, and connected Mediterranean and Paratethys. Right panel: freshwater budget values (Sv) discussed in the text. Bottom panel: 22 climate simulations and corresponding age.

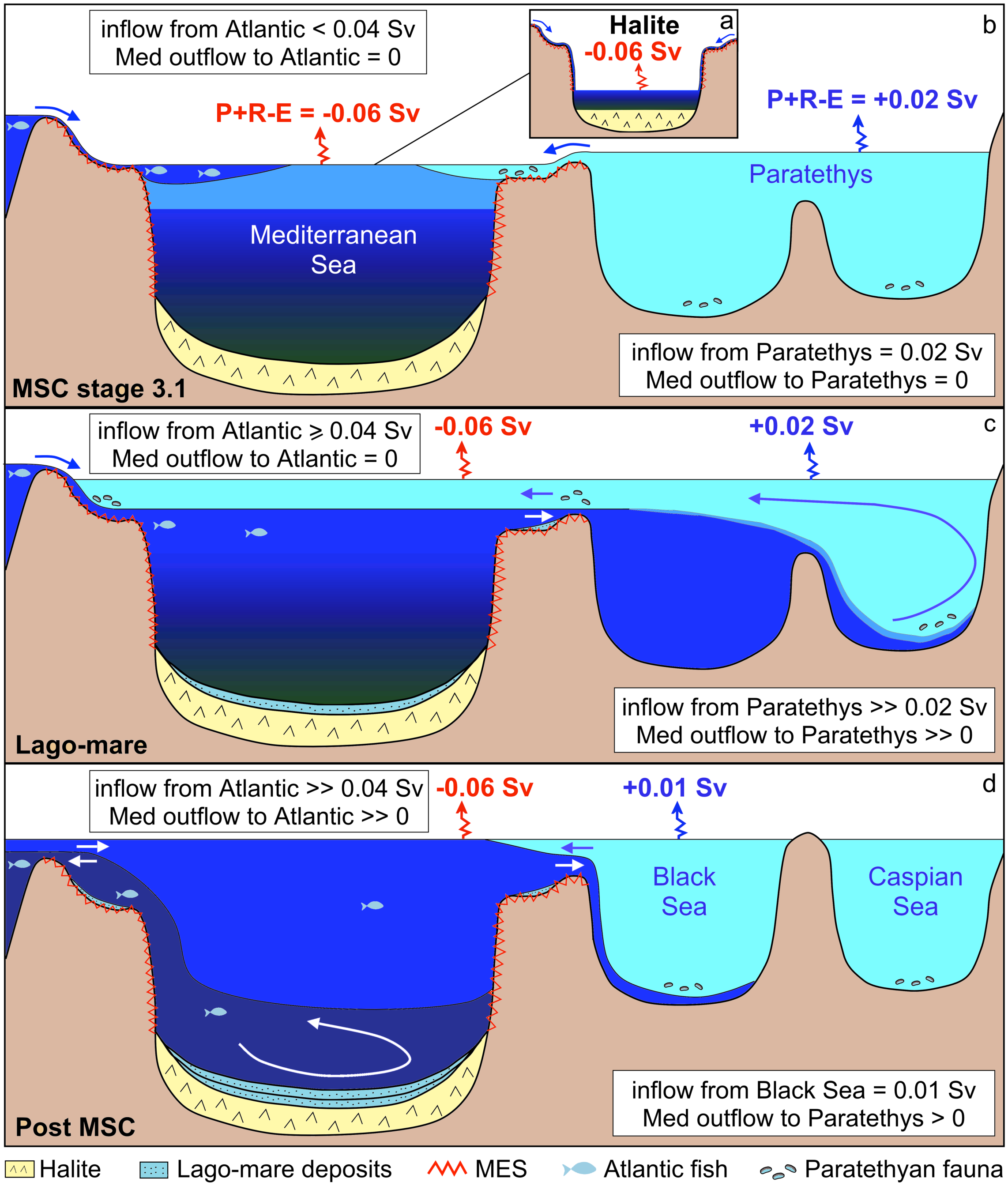


Figure 2. (a) Partially desiccated Mediterranean basin during Halite stage (inset of panel b); the exact height of the base-level fall is unknown. Proposed scenarios following partial desiccation and halite precipitation for (b) stage 3.1 of the Messinian Salinity

DOI:10.1130/G37646.1

Crisis, (c) Lago-mare phase with active overflow pump mechanism, and (d) reestablishment of marine conditions at the Mio-Pliocene boundary. Green and darker blue colors represent more saline water, decreasing in the lighter colors. Note that the presence of Lago-mare deposits is envisaged both in deep and marginal settings. The figure is schematic and basins' depths are not to scale. Values in Sverdrup represent the hydrologic fluxes into and out of the Mediterranean Sea (see Fig. 1b).